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Elastic and inelastic scattering of K^+-particles in nuclear emulsions

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With 5 figures in the text

SUMMARY

The frequency of elastic and inelastic K^+-particle scattering and the energy loss in inelastic scattering have been studied at a K-particle energy of 80–120 MeV. 32.5 m K-particle track has been followed. The frequency of elastic scatterings in the angular interval 12°–20° indicates a repulsive nuclear potential of about 10 MeV if the optical nuclear model is used. The mean free path for inelastic scattering (including charge exchange events) is equal to 1.12 ± 0.23 m, corresponding to a total cross-section of 181 ± 37 mb. One $K^+ + P$-collision has been found. The scattering angle for the K^+-particle is 57° in the centre of mass system.

Introduction

The forces between K-particles and nucleons are best studied in experiments where the mesons interact directly with free nucleons. But the experimental level, where more extensive experiments with K-particles and free nucleons can be made, has not yet been reached. Much information about the forces can however also be obtained from a study of the interaction between K-particles and nuclei. Measurements of elastic and inelastic scattering in nuclear emulsions (1–6) can, accordingly, give some information about the elementary K-particle-nucleon processes.

The present paper describes an investigation of the scattering of 100 MeV K^+-particles in nuclear emulsions. The aim of the work is to extend the results of scattering measurements already made at this energy.

Exposure

The emulsions have been exposed at the Berkeley Bevatron. 6.2 BeV protons hit a Cu-target and produced a large number of strange particles. K^+-particles, leaving the target at 90° relative to the proton beam, were used for the exposure after having passed an analyzing magnet which selected particles with a momentum of 455 MeV/c. Before reaching the stack the beam passed through a 2.5 cm thick Al-absorber.

The beam of positive particles reaching the emulsions was composed of protons, K^+-particles and π^+-mesons. The protons had a mean range in the emulsions of less than 1 cm. The π-mesons, which gave tracks of nearly plateau density, passed through the emulsions. The K-particles left the heavy proton exposure with an energy loss of about twice the minimum energy loss and passed through the stack (10 emulsions with the dimensions 7.5 cm × 7.5 cm × 600 μ).

In a stack exposed in this way it is impossible to prevent the appearance of a comparatively large number of background tracks having approximately the same grain density and the same direction as the K-particle tracks. If each K-particle can be followed to the point where it stops and can be identified by its decay, no mistake concerning the identification will be made. In this case, however, the decay points did not lie in the emulsions used and identification was impossible without making measurements of ionization and Coulomb scattering. All events studied and described in this paper have therefore been identified by such measurements.

Scanning procedure

In a study of scattering the scanning procedure must be chosen in such a way as to prevent as far as possible any bias against events which are difficult to find. Scanning along the tracks (7) which has a minimum bias of this kind should therefore be used. But as identification by following a track to its end was impossible in this case the ordinary method of track scanning was slightly modified.

A line just beyond the proton endings and at right angles to the particle beam was scanned for crossing tracks possessing the grain density and the direction to be expected for K-particles. When such a track was picked up, it was followed to the point where it left the emulsion. At this point a new track with grain density and direction expected for a K-particle was picked up and followed and so on until the scanning reached a line determined by the lower limit of the energy interval studied.

Essentially two sources of error appear in this scanning procedure concerning the total length of the tracks scanned.

1. Background tracks, mostly proton tracks, are sometimes followed instead of K-particle tracks. The number of nuclear interactions of such particles have been counted, and from a knowledge of the mean free path of these particles in nuclear emulsions ($\simeq 30$ cm) it has been possible to correct the total track length for this background.

2. In a scanning procedure of this kind, which picks up tracks irregularly, it is impossible to avoid a track or part of a track being sometimes followed more than once. The probability for double scanning has been appreciably reduced by using only a minor part of the total number of K-tracks in the emulsion. The remaining double scanning, which nevertheless exists, has been corrected from the number of K-particle events which have been observed more than once.

After correction in accordance with these sources of error the total K-particle track length is 32.5 ± 3.0 m.

The energy interval studied is 80–120 MeV with a mean energy of the interactions of 99 MeV.

The energy interval is enclosed by lines on the emulsions determined from relations between K-particle energy and position in the emulsion. Energy straggling and scattering have caused a few events with energy below 80 MeV or above 120 MeV to fall in this region. They have been measured and are included in the material.

Measurements

Events were recorded during the scanning if the track showed a scattering with an angle of at least 12°. Some difficulties in finding events with a small scattering angle and a corresponding reduction of scanning efficiency will be discussed later. A K-particle was as a rule identified before it scattered by measurements of grain density and Coulomb scattering. The small angle scattering measurements were made according to the angular method as discussed in detail by Goldschmidt-Clermont (8). The microscope used for the scanning moved satisfactorily in both x- and y-directions and could be used directly for the scattering measurements. The method is advantageous as it is not necessary to adjust the track in a given direction before the measurements.

The Gell-Mann Pais scheme does not allow any disappearance of a K-particle with strangeness $S = +1$ in a fast reaction such as a scattering. As the rule has been very carefully tested and always found valid, I did not find it necessary to make a new identification after the scattering except in a few cases. These exceptions are such events where the energy loss is very large (at least 50 %) and where it is not possible to decide directly by inspection of the grain density whether a track emerging from the point of collision is made by the K-particle or a proton from the excited nucleus. Charge exchange reactions showing evaporation prongs are included in these exceptions.

The energy of the K-particle has been determined by grain counting. About 700 grains have been counted in each energy determination giving an error slightly above 3 % in the grain density. A correction has been applied for the difference in the degree of development at different depths. The small change in energy and ionization along the interval used for grain counting has also been taken into consideration.

The relation between energy and grain density in the emulsions has been determined by grain counting tracks of unscattered K-particles the energy of which it has been possible to calculate. The momentum and the rate of change of the momentum across the particle beam were known from the conditions of exposure giving the energy of the K-particles when reaching the Al-absorber. From the relations between energy and range in the Al-absorber and in the emulsion it was then possible to calculate the mean energy of the K-particles in each point of the emulsion. Tracks of K-particles with energies between 40–150 MeV are found in the stack and used for the calibration. K-particle energies below 40 MeV have been determined by gap-counting instead of grain-counting with calibration against stopping proton tracks.

The error in the grain density–energy relation emerging from the limited number of calibration points is very small. But there does not seem to be a complete constancy in the degree of development throughout the whole stack, which gives an error larger than the pure statistical error and is difficult to estimate. The total calibration error does not however seem to exceed 10 MeV. Small systematic errors in the energy calibration are not very important for a determination of the relative energy loss in a scattering as the error often influences the energy determination in the same way before and after the scattering.

A systematic error in the grain density determination of importance for tracks of scattered K-particles with large dip is caused by the uncertainty in the shrinkage factor of the emulsion. The factor (2.3) is determined from measurements of the thickness of the processed emulsion and the assumption that the thickness was 600 μ at the exposure and is accordingly not very accurate. The error in $\Delta E/E$ for tracks which are approximately at right angles to the horizontal plane may be as large as 15–20 %, but the number of tracks with such an unfavourable direction is extremely small and the error will not influence the discussion of the results.

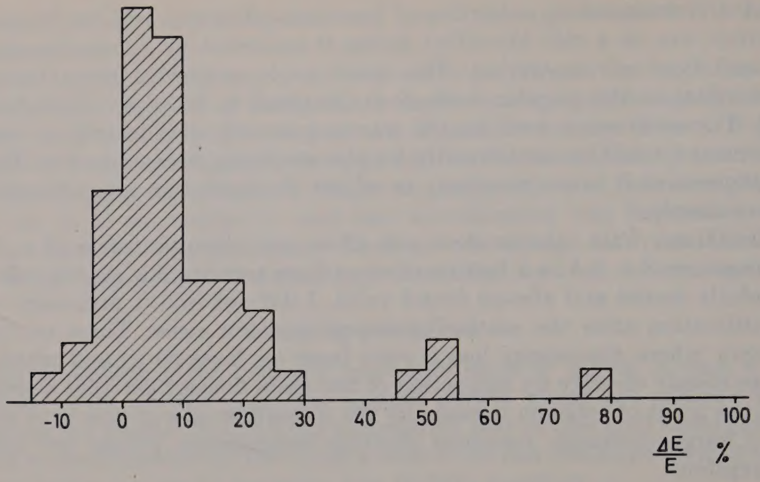

Fig. 1. The distribution of the relative energy losses for scattering angles exceeding 12°.

Experimental results

Fig. 1 shows the distribution of the relative energy losses $\Delta E/E$. ΔE is equal to the energy loss and E the energy before the scattering. The distribution is dominated by the elastic or nearly elastic events with $\Delta E/E \simeq 0$. A collision between a K-particle and a nucleus in the emulsion without any excitation is perfectly elastic only in the centre of mass system. The energy loss in the laboratory system is however very small (with few exceptions < 1 MeV), much smaller than the errors inherent in the measurements.

The distribution in Fig. 1 is unsymmetrical, with a tail against large $\Delta E/E$ values. This tail contains the inelastic events. There is no easily determined limit between the elastic and the inelastic scatterings. One way to divide the events into one elastic and one inelastic group is to assume that the elastic events are distributed symmetrically around $\Delta E/E \simeq 0$. All events not belonging to this symmetrical distribution are assumed to be inelastic. Such a division gives two groups with nearly the same number of scatterings.

Another division suitable for a comparison with some experiments on π-meson scattering can be made. If the lower limit for inelastic scattering is chosen equal to $\Delta E/E = 0.15$, the number of inelastic scatterings will be approximately 25 % of the total number of scatterings. A similar investigation on 100 MeV π-mesons by Bernardini, Booth and Lederman (9) gives about 60 % inelastic scatterings. This large difference in inelasticity indicates a difference in the nuclear interaction for the two kinds of particle.

One K-particle collision with a proton has been found. The collision data are the following

K-particle energy before the collision	115 MeV
Scattering angle in the lab-system	37°
Scattering angle in the c.m. system	57°.

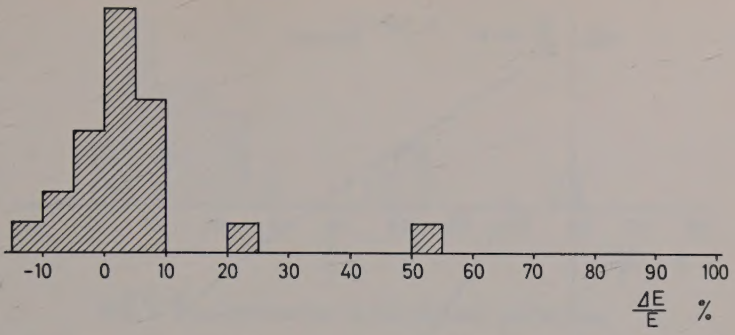

Fig. 2. The distribution of the relative energy losses for scatterings in the interval 12°–20°.

Pedretti's curves (10) have been used for the transformation from the lab. system to the centre of mass system and also for the check of momentum balance and angles in the collision, proving that the event really was a $K+P$-collision.

Elastic scattering in the angular interval 12°–20°

Fig. 2 shows the distribution of $\Delta E/E$ for scatterings in the interval 12°–20°. The elastic scatterings have a mean value $\Delta E/E = 0.01$ and seem accordingly to be true two-particle collisions between the K-particles and the nuclei of the emulsion.

The probability of finding a scattering in this interval in track scanning is not unity but a function of the direction of the K-track after the scattering. Two examples will show the reason. If a particle is scattered in the horizontal plane it is very easy to see its change of direction and the probability of finding the scattering is practically unity. But if the scattering takes place in the vertical plane the probability will be much smaller, especially if the event lies near the glass or the surface. This scanning bias has been eliminated by multiplying the number of events found by a factor 1.5. The factor has been determined from the angular distribution of the scatterings observed.

The number of elastic scatterings in Fig. 2 is 20, which will be increased to 30 after the elimination of the scanning bias.

Costa and Patergnani (11) use the optical model for the nucleus in a theoretical study of elastic K-particle scattering. It is assumed that the K-particle is scattered against a potential

$$V = V_c + V_n.$$

The potential is composed of two parts, one representing the Coulomb potential (V_c), and the other the nuclear potential for the specific interaction between the K-particle and the nucleus (V_n). V_n is assumed to be constant inside nuclear matter and equal to zero outside the nuclei. In the general formulation of the theory, V_n is a complex potential but the properties of the K^+-particles are such that the imaginary part can be neglected (11). Starting from this potential, Costa and Patergnani have computed the differential cross-section for elastic scattering as a function of the scattering angle. The expression for the cross-section contains two parameters, the nuclear potential V_n and the kinetic energy of the K-particle.

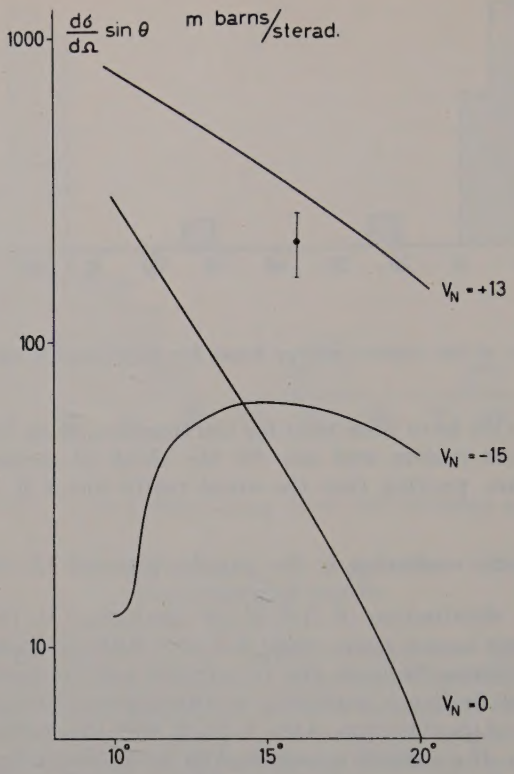

Fig. 3. The differential cross-section of elastic scattering in the interval 12°–20°. The K-particle energy is 100 MeV. The curves are drawn for three different nulcear potentials between the K-particle and the nucleus; 1) a repulsive nuclear potential $V_n = 13$ MeV, 2) a pure Coulomb potential $V_n = 0$, 3) an attractive nuclear potential $V_n = -15$ MeV.

Fig. 3 shows three examples of the differential cross-section for a K-particle energy of 100 MeV. The curves are drawn for

1. a repulsive nuclear potential $V_n = 13$ MeV
2. a pure Coulomb potential $V_n = 0$
3. an attractive nuclear potential $V_n = -15$ MeV.

From the scattering measurements reported here the cross-section can be computed to

$$\frac{d\sigma}{d\Omega} \sin \theta = 226 \pm 54 \text{ mb.}$$

This result has been plotted in Figure 3. It can be interpreted either in terms of a repulsive potential somewhat less than 13 MeV or an attractive potential larger than 15 MeV. The distribution of the measurements favours the repulsive potential. The result is in accordance with most measurements on K-particle scattering between 40 and 160 MeV hitherto published (2, 3, 4, 5, 6).

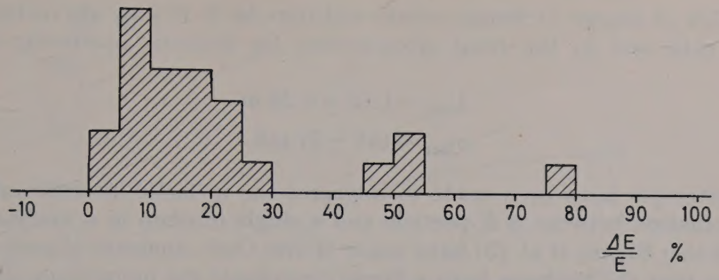

Fig. 4. The distribution of the inelastic scatterings.

Inelastic scattering

There is no clear division between elastic and inelastic scatterings in the experimental material. If the number of inelastic scatterings is wanted, the separation must be done partly by statitical methods. Fig. 4 shows the distribution of the inelastic scatterings. They have been obtained from the total number of measurements from which an elastic group has been subtracted. These elastic scatterings belong to a symmetrical distribution around $\Delta E/E=\varepsilon$, where ε has a small positive value determined by the energy transfer in the collisions. The group includes the elastic scatterings in Fig. 2 and also elastic scatterings with the scattering angle exceeding 20°.

The correction for scanning losses is negligible. The reason is that the number of inelastic scatterings is small in the angular region where the scanning losses are appreciable.

The number of inelastic events is 24 giving a mean free path for inelastic scattering in nuclear emulsions equal to

$$\lambda_{\text{inel}}=1.35\pm0.30\text{ m}.$$

The cross-section for inelastic collisions can be calculated directly from the expression $\sigma_{\text{inel}}=213/\lambda_{\text{inel}}\cdot\sigma_{\text{inel}}$ is expressed in millibarns and λ_{inel} in metres. The density of the emulsion has been put equal to 3.83 g/cm^3.

$$\sigma_{\text{inel}}=158\pm33\text{ mb}.$$

These figures do not include charge exchange events following the reaction $K^{+}+$ bound neutron $\rightarrow K^{\circ}+$ bound proton.

Seven cases which may be classified as charge exchange events have been found. Associated proton tracks from the excited nucleus are found in three of them and there is no doubt about their identity. In four cases "stops" have been observed without any visible emerging track. These events are either charge exchange events or decays in flight into a relativistic secondary with a direction which makes observation very difficult. The emulsions are however strongly developed (plateau value 26 grains/100 μ) on account of which the probability of missing a secondary must be small. An estimate of how "stops" are distributed between decays and charge exchanges has been made by Bhowmik *et al.* (12). In emulsions with a plateau value equal to 16 grains/100 μ they find that $^2/_3$ of the "stops" are decays and $^1/_3$ charge exchange events. In consequence of the difference in development it seems reasonable to assume that two of the four "stops" are charge exchange events.

The number of charge exchange events will thus be 5. If they are included in the mean free path and in the total cross-section for inelastic scattering the result will be

$$\lambda_{\text{inel}} = 1.12 \pm 0.23 \text{ m}$$

$$\sigma_{\text{inel}} = 181 \pm 37 \text{ mb.}$$

Several attempts have been made to interpret the inelastic interactions in terms of simple collisions between a K-particle and a single nucleon in a nucleus. Cocconi *et al.* (4) and also Biswas *et al.* (3) have made Monte Carlo analyses of such collisions. They assume that the nucleons have a Fermi degenerate gas momentum distribution and calculate the energy loss and the angular distribution of the scattered K-particles.

The calculations do not fit the experimental results very well. The disagreement is especially large for events with large scattering angles. The calculations require a large loss of energy but the experiments show a large number of events with very small energy loss. For inelastic scatterings larger than 90° the mean value of $\Delta E/E$ in this paper is equal to 0.39 in good accordance with other measurements. The Monte Carlo calculations by Cocconi *et al.* give the mean value $\Delta E/E = 0.61$.

It is obvious that a better agreement with the experiments can be reached if some assumptions are made for the parameters in the calculations; the cross-section may be a function of the scattering angle, the Fermi momentum distribution may be substituted by a distribution with momentums exceeding 215 MeV/c, the cross-section may be a function of the relative velocity between the K-particle and the nucleon, a.s.o. But there are no experiments supporting the assumptions and such calculations are accordingly a little dubious.

In the discussion of the elastic scattering a repulsive nuclear potential of about 10 MeV was needed for the explanation of the cross-section. Such a potential will reduce the percentage energy loss in inelastic collisions and the disagreement between the calculations and the experiments will be reduced to a degree depending on the size of this potential. The total repulsive potential ($\simeq$ 20 MeV) determined from the elastic scattering seems however too small to give a satisfactory explanation of the inelasticity in several events. The explanation may be that the optical model calculations give a repulsive potential which is too small. But there is another possibility which also should be taken into consideration.

Anderson *et al.* (13) and also Biswas *et al.* (3) call attention to the possibility that the K-particle does not interact with a single nucleon but with a group of nucleons in the nucleus. Such a multinucleon interaction can very well permit large angle scatterings with small energy losses.

Strange particle interactions with groups of nucleons have been observed earlier in several cases. Some examples will illustrate such reactions. The reaction between a fast K^+-particle and a carbon nucleus according to $K^+ + \text{C}^{12} \rightarrow K^+ + 3\ \text{He}^4$ is observed (13, 14). Berthelot *et al.* (15) have found interactions between K^--particles and nuclei, giving decay products with energies which are possible to explain kinematically only if the reaction takes place between the K-particle and more than one nucleon. The number of hyperfragments in K^--reactions with nuclei in emulsions (16, 17) is very high in comparison to the number expected from the frequency of heavy fragments in nucleon-induced stars (18) with the same prong-number distribution as the K^-stars. The examples given will show that it is not quite meaningless to discuss the inelastic K^+-particle scattering in terms of multinucleon interaction.

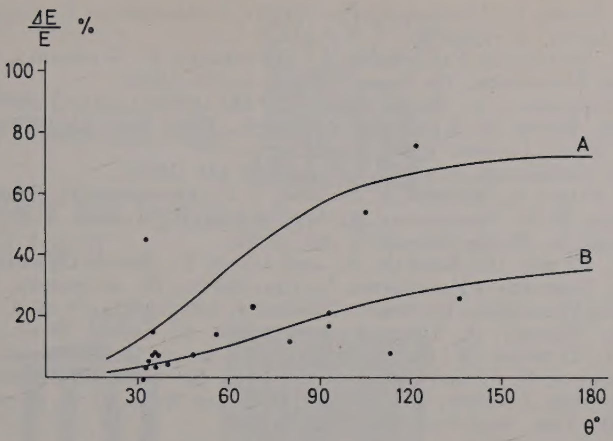

Fig. 5. The measurements of $\Delta E/E$ for scatterings exceeding 30°. Curve A shows the energy loss to be expected when a K-particle collides with a nucleon at rest in a region with a repulsive potential of 20 MeV. Curve B shows the energy loss in a collision with four nucleons in the same potential.

Fig. 5 shows the measurements of $\Delta E/E$ for angles exceeding 30°. Curve A shows the energy loss to be expected when a 100 MeV K-particle collides with a nucleon at rest in a region with a repulsive potential of 20 MeV. Depending on the motion of the nucleons it is of course to be expected that neither the measurements nor their mean value should fall on this curve. But the discrepancy seems very large and the simple two-particle interaction is difficult to accept, at least in some cases. Curve B has been calculated for a collision with a group of four nucleons in the same repulsive potential. This curve is a much better fit to most measurements. It is however very difficult to understand how such a multinucleon collision takes place, especially if we take into consideration the experiments which indicate a shorter range for the K^+-nucleon forces than for nucleon-nucleon forces. But, on the other hand, one must remember that the independent particle model is only an approximation of the nucleus, and that the distribution of the nucleons has not been taken into consideration.

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